

Design and experiment on a mini cascade thermoacoustic engine

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Abstract

A miniature cascade thermoacoustic engine had been designed and tested, which length was about 1 m, operating at 500 Hz. Pilot study and experimental results shown a rather good agreement between measured and calculated pressure fields and temperatures distributions in the thermoacoustic engine. The peak-to-peak value of the acoustic pressure was 0.02 MPa at the 1.8 MPa charged pressure of helium. Some efforts had been made to extend the traveling-wave region based on the analysis of the acoustic impedance.

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1. Introduction

The efficiencies of thermoacoustic devices have been improved essentially from the initial standing-wave type to traveling-wave type. But actual efficiency of the traveling-wave engine proposed by Cerpely [1] was low for serious viscous and heat dissipation, which was due to the low acoustic impedance of gas in a pure traveling-wave region. Because the viscous dissipation and heat transport due to imperfect thermal contact in a regenerator were both inverse proportion to the square of the acoustic impedance. Cerpely's idea was carried out by a thermoacoustic-stirling hybrid engine, developed by Swift etc., which yielded 42% of the Carnot efficiency. This toroidal topology had high fabrication costs, and extra, it needed to provide an adjustable jet pump to suppress Gedeon streaming around the torus. To eliminate Gedeon streaming, reduce fabrication costs and increase efficiency simultaneously, a cascaded thermoacoustic engine was built experimented [2]. We realized that the practical acoustic field in the resonators was the commixture of standing-wave and traveling-wave, and the traveling-wave region (TWR) existed in the standing-wave acoustic field of the

resonator, which had high specific impedance. So, regenerator unit could be arranged in TWR, that would upgrade the efficiency of whole system.

2. Device design

The resonator embodiment was the main decision in the design of cascade engines. The traveling-wave acoustic field with high impedance was necessary to get effective thermoacoustic conversion. A dumbbell type of half wave-length resonant system had a region that met the requirements. Acoustic field in the system could be regarded as the superposition of two reversed acoustic plane waves, denoted as p_r and p_i , respectively. Formula (1) and (2) could be divided into two components, standing-wave component (SWC) and traveling-wave component (TWC), respectively, where $p_{sa} = p_{ia} + p_{ra}$ was the maximal amplitude of the standing-wave, p_{ia} and p_{ra} were the pressure amplitudes of the reversed waves in the resonant system, $p_{ta} = p_{ia} - p_{ra}$ was the maximal amplitude of the traveling-wave, ω was the angular frequency, and k was the wave vector, the coordinate origin of x located at the center of the resonator tube.

$$p = [p_{sa} \cos kx - ip_{ta} \sin kx]e^{i\omega t} \quad (1)$$

$$u = \frac{1}{\rho_0 c_0} [p_{ta} \cos kx - ip_{sa} \sin kx]e^{i\omega t} \quad (2)$$

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Table 1
The simulation calculation comparison with different design projects

Project	1st η (%)	2nd η (%)	3rd η (%)	Total η (%)	L (mm)
1	17.57	10.22	11.01	11.75	35
2	14.06	20.00		12.14	20
3	16.13	28.92		18.50	75
4	19.98	34.06		22.74	70

Under such configuration of acoustic system, the phasing by which pressure leading velocity at the center was zero, that was called the sweet spot, which was the minimum of the local velocity. The spacing between positive/negative 45° phasing was defined as the effective TWR [2], for example, in 1 m long and 100 mm diameter resonator, the TWR length was only 7.6 mm. High impedance was an important condition for high thermoacoustic efficiency. Cerpley indicated that 72% of the Carnot efficiency could be reached if the impedance was about ten times larger than the local special impedance. From formula (1) and (2), it was easily concluded that the impedance near the center of resonator was sufficient high. For high local acoustic impedance, the diameter ratio of thermoacoustic unit tube to resonator tube was 1.69, optimizing for the minimum dissipation of acoustic power.

The stages number was other important issue. The cascaded efficiency was determined by τ defined as T_H/T_C and stages number N with formula (3) [2]. It was about 26% for one standing and one traveling-wave stage typically.

$$\eta \approx \frac{\tau^N}{2 + 3\tau^N} \quad (3)$$

In our design, four projects were contrasted to find the optimization. The first project was composed one standing-wave stage and two traveling-wave stages. The others were two stages, but with different local dimensions to extend the traveling-wave region. The simulated efficiency η and the TWR length (L) for different projects were listed

in Table 1, respectively. The calculated L was often too small to arrange the regenerator. Therefore, adjustments of the location and the length of TWR were very important. The sweet spot could change with the variety of the terminals volume, with entrance impedance of terminals and heater position in the duct. According to the lumped impedance network approximately, shown as Fig. 1, the sweet spot was around velocity node, the local inductance could be ignored, and the local acoustic compliance mostly determines the traveling-wave property. The TWR length would be greater while the compliance being smaller. The calculated results in Fig. 2 approved of the conclusion, the TWR length could be extended.

3. Experiments

The present engine consisted of a regenerator and a stack sandwiched by two heat exchangers, respectively. The stack was diameter 28 mm, length 65 mm, screen 80 meshes, heater power 150 W. The regenerator was diameter 22 mm and length 25 mm, screen 200 meshes, heater power 120 W. The total length of the system was 1 m and opera-

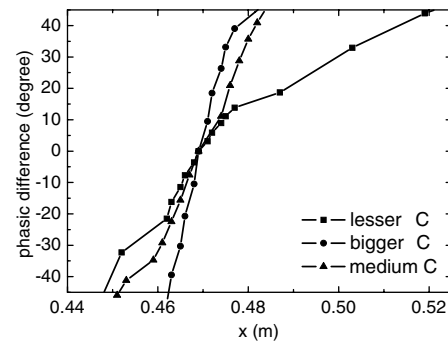


Fig. 2. The phasing between pressure and velocity for different design projects. C, local acoustic compliance near the traveling-wave region.

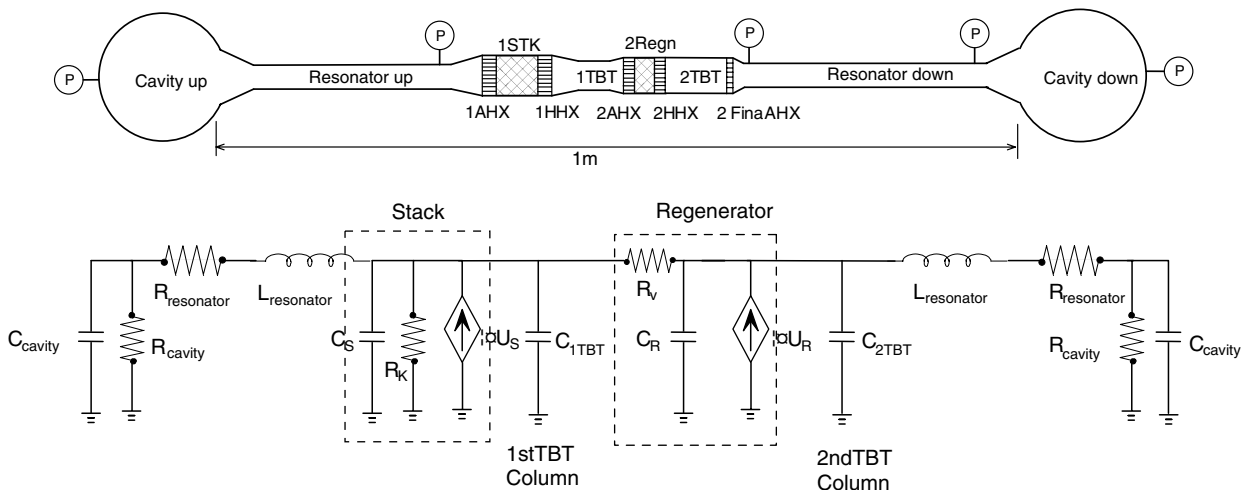


Fig. 1. The cascade thermoacoustic engine and Lumped-element model. AHX, ambient heat exchanger; HHX, hot heat exchanger and Regen, regenerator.

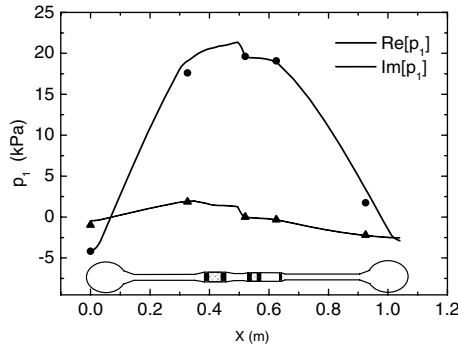


Fig. 3. Components of pressure distribution for a typical operating point. Dots were measured values and lines were calculations.

tion at 500 Hz. The apparatus and acoustic network were shown in Fig. 1.

The arrangement of experimental consisted heater power source, cooling water system, five pressure transducers denoted in Fig. 1, which could calculate acoustic power by two-sensor method.

Experiments were made at heater power from 60 to 150 W, and average pressures from 0.8 to 1.8 MPa. The measured and calculated pressure were shown in Fig. 3, in which dotted points were measured results and lines were calculated results. The agreement between them was rather good. According to the pressure measurements by a phase-lock amplifier, the acoustic power produced in the standing-wave stage was estimated by two-sensor method with formula (4) [3].

$$E_2 \approx \frac{\pi r^2}{4\omega\rho\Delta x} \left[(1 - \delta_v/r) |p_A| |p_B| \sin \phi + \frac{\delta_v}{2r} (|p_A|^2 - |p_B|^2) \right] \quad (4)$$

Accordingly, the heat efficiency (the ratio of acoustic power to heater power) was about 13.5% in experiments, which was simulated about 20% by model of the parallel stack. There were some requirements in using the two-sensor method to measure the acoustic power output from the traveling-wave stage. For example, the midpoint between two-sensors should be close to the velocity antinode [3]. Because the fourth sensor was near the pressure node, it could not determine the acoustic power output. Improved

measure methods with load applied to the bottom of the apparatus would be performed in future research. Further modification for turbulent loss and Rayleigh streaming effect on the thermal buffer tube (TBT) was planned by setting a few stainless steel screens as flow straighteners at TBT.

Due to more than one stack in the resonator, the onset of the self-excitation of the apparatus was often rather difficult. By fine design, there was no problem in our experiments. The measured onset temperature gradient was 8.5 K/mm, which exceeded the critical value $\nabla T_{\text{crit}} = 1.9 \text{ K/mm}$.

4. Conclusions

A half wave-length resonator was designed, which had a TWR in the middle of the resonator with high impedance for high efficient thermoacoustic conversion. The configuration of the resonator determined the proportion and impedance of TWR. The design processes compared four projects and adopted the optimized cascaded stages number and dimensions of the resonator. The adjustment of the local compliance was approved to be an effective method to extend TWR. The onset temperature condition was easy reached in our experiment, which approved rationality of the design. The agreement between predicted acoustic field and the measured acoustic field was good.

Acknowledgements

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